1976

# Evaluation of Composite Vane Materials for Rotary Sliding Vane Compressors

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ABSTRACT

The physical performance characteristics of composite materials used for vanes in rotary, sliding-vane compressors, in general, are several orders of magnitude more difficult to quantify for design purposes than most homogeneous materials. This arises from the numerous variables that influence the response of these materials under the severe environmental conditions existing in such compressors. It is not the purpose of this report to develop a statistical analysis for predicting performance characteristics, but rather to enhance the understanding of the behavior of certain composite materials through the presentation of experimental data.

A number of resin-reinforced materials were examined to determine specific physical properties that are believed to influence their performance in rotary, sliding-vane compressors. All these reinforced materials are commercially available from various plastics manufacturers and primarily utilize thermoplastics such as Torlon polyamid-imide (AMOCO), 2080 polyimide (Upjohn), Kerimid polyimide (Rhodia), Ryton polyphenylene sulfide (Phillips), and special phenolics. These resins were reinforced primarily with various grades of asbestos cloth and felts resulting in laminated specimens, however, other materials, such as fiberglass cloth, were also used.

The physical properties presented include the flexural strength, flexural modulus, thermal expansion coefficient, thermal stability, and friction/wear characteristics. The results from thermal aging tests are also included and establish the flexural strength degradation at elevated temperatures. Acoustical emission tests, accompanied by physical examinations of the test specimens, were used to correlate the bending failure mode with the stress-deflection obtained on the Instron tester.

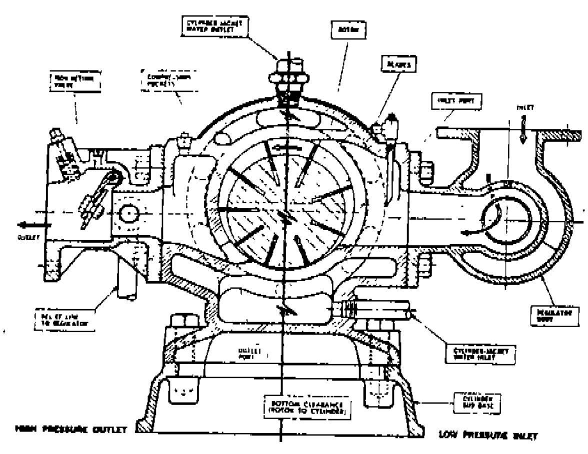



Fig. 1

INTRODUCTION

The Fuller rotary compressor, shown in Figure 1, is representative of sliding, multivane type positive displacement machines. All these compressors have a rotor arranged eccentrically within a cylinder on the same vertical centerline. Blades, fabricated from composite materials, slide freely within milled slots in the rotor and are forced outward during rotation by centrifical force. During operation, these composite blades are subjected to numerous, complex dynamic forces and, as a result, are most susceptible to failure. An excellent dynamic analysis of a moving vane was presented by Edwards and McDonald at the 1972 Purdue Compressor Conference.

In addition to dynamic loads, these blades are subjected to elevated temperatures that effect wear characteristics and the strength of the composite material, particularly when operated for long periods of time. Laboratory experiments have also shown that thermal gradients exist within the blade and may vary from 425°F at the root to 350°F at the tip of the blade which rides against the water cooled cylinder.

BACKGROUND

Until the early sixties, the standard composite blades, fabricated from a modified phenolic resin reinforced with AA asbestos cloth as a laminate, performed admirably. Some compressors were known to have operated continuously for more than 20,000 hours, or roughly two years, without ever requiring a blade change. Toward the end of that decade, however, the incidence of blade failure rose dramatically. The blade manufacturers were at a loss to explain this rapid deterioration in blade performance, and the Research and Development Department was called in to investigate the problem. Compressor endurance tests revealed that life of the standard phenolic/asbestos cloth laminated blade had decreased from the well documented 20,000 hours to less than 1500 hours. This initiated a blade development program which provides the substance for this paper.

BLADE FAILURE MODE

The modified phenolic resin/AA asbestos cloth laminated blades were inspected at various time intervals while they were undergoing endurance tests in the high-pressure stage of a laboratory test compressor. Microscopic examination of these blades revealed the progressive development of cracks or crazing in the phenolic resin within each small matrix formed by the intersection of the fibers in the asbestos cloth. This is shown in Figure 2. These cracks were more pronounced at the root of the blade than at the tip and conforms to the thermal gradient that exists in the blade, the blade temperature being greater at the root. The cracks continued to increase in severity with time and resulted in, what ultimately became, a standard failure mode characterized in Figure 3. The primary fracture occurred along the length of the blade at the 40% standout point (i.e. closer to the blade tip) and is indicative of the highest point of stress. A secondary fracture occurred along the width of the blade which precipitated total failure.

The failure mode of the composite blades can be directly attributed to the repeated or cyclic imposition of both mechanical and thermal stresses. For this reason, the flexural strength and its thermal degradation with time is considered of prime importance when evaluating candidate compressor blade materials.

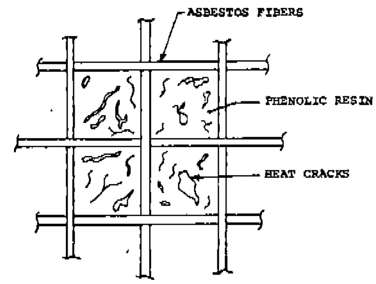



Figure 2

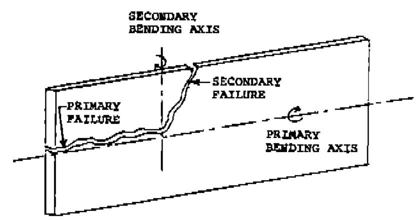



Figure 3

FLEXURAL STRENGTH

The failure characteristics of composite materials are more difficult to quantify than most homogeneous materials. This arises from the numerous variables that influence the response of the material and results in data which exhibits considerable scatter. For this reason, all the physical data presented in this paper are the mathematical average of tests conducted on at least three, and in most cases five, specimens.

The flexural properties and thermal expansion coefficients of a number of composite materials appears in Tables 1 and 2. Table 1 covers phenolic resins laminated with different grade and type asbestos reinforcement, and Table 2 covers some of the other resin reinforced composites tested.

The plastics fabricators who supplied the composite materials presented in this paper are too numerous to list. The phenolic resins are usually proprietary formulations of each individual plastics supplier. The resins that were tested are commercially available under the trade names of Torlon polyamide-imide (AMOCO), Ryton polyphenylene sulfide (Phillips), 2080 polyimide (Upjohn), Kerimid polyimide (Rhodia), and P13N polyimide (Ceba-Geigy).

Tables 1 and 2 illustrate that the material used to reinforce the resin significantly influences its room temperature mechanical properties, provided a good bond can be achieved between resin and reinforcement. For example, it was not possible to achieve a good bond between Ryton polyphenylene sulfide (PPS) and either glass or asbestos cloth when attempting to laminate this combination (see Table 2). Injection moldings using Ryton with chopped, glass and/or asbestos fibers, however, produced excellent results.

The way a plastics fabricator modifies his phenolic resin through the addition of extenders and fillers can, significantly influence the properties of the composite material. The four asbestos felt materials listed in Table 1 illustrate this point. The AAAA asbestos felt is identical to the 9579 asbestos felt and the underwriter's grade of asbestos felt is identical to the 9517 asbestos felt (see Table 4). However, two different manufactures, each with their own phenolic resin formulation supplied these apparently identical materials. As can be noted, their flexural properties vary widely. In addition, the two different phenolic resins, although reinforced with identical materials, yields very different coefficients of thermal expansion. In light of these results, caution must be exercised when examining generalized data on phenolic reinforced composite materials.

TABLE 1

PROPERTIES OF REINFORCED THERMOSETTING RESINS

| Resin | Reinforcement | Process | Flex.Str. KSI | Flex.Mod. $10^6$ Psi | Them.Exp. $10^{-6}$ in/in/°F |
|---|---|---|---|---|---|
| Phenolic | AA Asbestos Cloth | Lam. | 18.3 | 1.9 | 6.5 |
| Phenolic | Underwriters Asb. Cloth | Lam. | 14.0 | 1.2 | 4.2 |
| Phenolic | Polyglass Cloth | Lam. | 12.5 | 0.9 | 6.0 |
| Phenolic | Special Glass Cloth | Lam. | 38.0 | 2.3 | 6.7 |
| Phenolic | Graphite Cloth | Lam. | 18.7 | 1.7 | 3.6 |
| Phenolic | Nomex Cloth | Lam. | 19.9 | 0.8 | 22.7 |
| Phenolic | Canvas Cloth | Lam. | 13.4 | 0.9 | 10.9 |
| Phenolic | Kevlar Cloth | Lam. | 37.9 | 2.4 | 2.2 |
| Phenolic | Carbitex Cloth | Lam. | 23.0 | 1.5 | 8.4 |
| Phenolic | Novatex Cloth | Lam. | 11.8 | 1.7 | 4.5 |
| Phenolic | AAAA Asb. Felt | Lam. | 20.8 | 1.8 | 8.5 |
| Phenolic | 9579 Asb. Felt | Lam. | 37.3 | 4.1 | 2.2 |
| Phenolic | Underwriters Asb. Felt | Lam. | 16.0 | 1.5 | 7.2 |
| Phenolic | 9517 Asb. Felt | Lam. | 28.0 | 2.7 | 2.8 |
| Kerimid | AA Asbestos Cloth | Lam. | 11.7 | 0.5 | 8.0 |
| Kerimid | Fine Weave AA Asb. Cloth | Lam. | 18.5 | 1.6 | 6.6 |
| Kerimid | Glass Cloth | Lam. | 77.0 | 4.4 | 5.4 |
| Kerimid | 30% Asb. Fibers 20% Graphite | Comp. | 12.2 | 1.6 | 10.1 |
| P13N* | AA Asbestos Cloth | Lam. | 29.2 | 2.0 | 4.2 |

*Polyimide similar to Kerimid Polyimide

TABLE 2

PROPERTIES OF REINFORCED THERMOPLASTIC RESINS

| Resin | Reinforcement | Type* | Flex.St. KSI | Flex.Mod. $10^6$ Psi | Therm. Exp. $10^{-6}$ in/in/°F |
|---|---|---|---|---|---|
| Torlon | 30% Glass Fibers | I | 18.5 | 1.5 | 7.7 |
| 2080 Polyimide | AA Asbestos Cloth | L | 15.2 | 1.3 | 4.4 |
| 2080 Polyimide | Underwriters Asb. Cloth | L | 7.4 | 0.5 | 6.1 |
| 2080 Polyimide | Glass Cloth | L | 30.6 | 2.3 | 6.3 |
| 2080 Polyimide | 70% Glass Fibers | C | 28.3 | 2.3 | 8.6 |
| Ryton PPS | 35% Carbon Fibers | I | 27.1 | 2.6 | 7.2 |
| Ryton PPS | 27% Carb.Fib., 23% Asb. Fib. | I | 24.3 | 2.6 | 8.7 |
| Ryton PPS | 30% Kevlar, 20% Graph. | I | 22.6 | 1.2 | 11.2 |
| Ryton PPS | 45% Asb. Fib, 5% Carb. Fib. | I | 12.0 | 2.5 | 12.8 |
| Ryton PPS | 40% Glass Fiber | I | 26.8 | 1.7 | 15.1 |
| Ryton PPS | AA Asbestos Cloth | L | 6.8 | 2.1 | 7.2 |
| Ryton PPS | Glass Cloth | L | 9.7 | 0.7 | 7.2 |
| Ryton PPS | AA Asbestos Felt | L | 17.0 | 2.1 | 5.3 |

*I - Injection Molded  C - Compression Molded  L - Laminated

## THERMAL STABILITY

Thermally stable composite materials are absolutely necessary if good performance is to be achieved in a rotary vane compressor. Depending upon the application, compressor gas discharge temperatures can vary from 250°F to over 375°F. Composite materials with a high thermal expansion coefficient can cause the blades to contact the cylinder heads at the higher temperature while creating a loss in volumetric efficiency at the lower temperature. For this reason, only those candidate blade materials whose thermal expansion coefficient is less than 7 x $10^{-6}$ in/in/°F can be considered for use in Fuller's compressors.

Another reason for good thermal stability arises from the existance of a temperature gradient along the width of the blade. The tip of the blade rides against the water cooled cylinder and is approximately 75° cooler than the root of blade in the rotor slot. The temperature at the blade root may exceed 425°F. This is because of the entrapment, and resultant compression, of gases beneath the blade as it slides back into the rotor slot. The effect on the blade is to have a greater material expansion along the length of the blade at the root than at the tip. This causes the blade to bow in a direction parallel to that of the compressor axis. Initially, there is a loss in volumetric efficiency until the blade wears in to conform to the straight wall of the compressor cylinder. This blade distortion problem can be reduced by using materials having a low coefficient of thermal expansion, but it cannot be eliminated. To achieve good volumetric efficiency, the blade must have some reasonable, but not excessive, wear rate.

## FLEXURAL RESPONSE CURVES

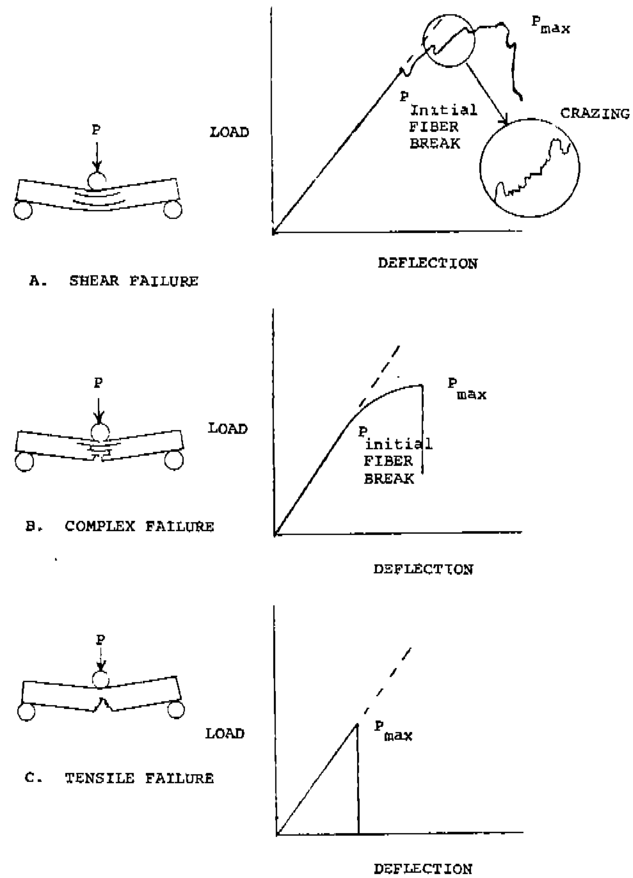
A great deal of information can be obtained by examining the stress-deflection curve generated by an Instron or similar test machine. For example, Figure 4 illustrates the correlation between the various types of bending failure modes and their respective stress-strain curves. In this figure, a shear failure mode is caused by interlaminar debonding, a complex failure mode is a combination of debonding and constituent failures, and a tensile failure mode is characteristic of brittle materials.

The deviation from the linear stress-strain response of laminated composites represents pronounced changes in the stiffness of the material caused by the fracturing of individual lamina. This was verified by simultaneously loading a phenolic/asbestos cloth laminated specimen in the Instron machine and recording the audible reports as the fibers broke. Invariably the first fiber break corresponded to the point where the stress-strain curve became non-linear.

A second phenomena known as crazing becomes prominent at higher stress levels. The term crazings is applied to the formation of small cracks in the resin material. This effect is caused by the application of mechanical loads to areas weakened by impurities, voids, or undesirable molecular chains and is aggravated by elevated temperatures. The crazing phenomena is recognizable in the stress-strain curve by the formation of a "knee" or dip in the curve and results from a substantial fiber failure in some critically loaded layer. Almost invariably it is a layer subjected to shear or transverse loading. Acoustically, there is a sudden rash of audible reports which taper off both in period and intensity. These audible reports are frequently masked by subsequent failures of other layers and appear on the stress-strain curve as secondary "knees" or dips superimposed upon the primary one.

## FRICTION AND WEAR

The coefficient of friction of almost all the materials examined varied between 0.09 and 0.13 when run against steel in an oil bath that was maintained at a temperature of 200°F. The only exception was Ryton polyphenylene sulfide whose friction coefficient varied between 0.03 and 0.06.




CORRELATION OF FAILURE MODE & STRESS-STRAIN

Figure 4

The wear rates obtained on composite materials actually run in the test compressor and those obtained on a Dow Corning Friction/Wear Machine are shown in Table 3. As can be seen there is a definite trend between the two results, however, more extensive testing is required to obtain a quantitative correlation.

Regardless of the resin, glass reinforced plastics will not perform well in Fuller's partially lubricated, compressor due to excessive wear rates. A compression molded, 2080 polyimide reinforced with 70% chopped glass had a wear rate of approximately one-half inch per 100 hours of operating time in the high pressure stage of Fuller's test compressor. Such wear rates cannot be tolerated when blade width nominally vary between two and four inches.

TABLE 3

WEAR CHARACTERISTICS

| Composite Material | Compressor Wear Rate mils/1000 hrs. | Dow Corning Wear Rate in./1000 hrs. |
|---|---|---|
| Phenolic/AA Asb. Cloth | 37.2 | 1.70 |
| 2080 Polyimide/AA Asb. Cloth | 5.4 | .86 |
| Phenolic/Und. Asb. Cloth | 5.1 | .79 |
| Kerimid Polyimide/305 Asb. Fiber 20% Graphite | 2.8 | .61 |

Of all the reinforcements examined, asbestos, in one form or another, has proved to yield the most desirable wear characteristics. In addition, asbestos tends to increase the thermal stability of the composite, thus enhancing its desirability.

THERMAL DEGRADATION

The degradation of mechanical properties due to thermal aging at an elevated temperature is shown in Figures 5 and 6 for the modified phenolic laminated materials and Figures 7 and 8 for the reinforced polyimide composites. The flexural strength data was obtained by thermally aging the specimens at 220°C for various periods up to 500 hours or 21 days and then fracturing them at 220°C in the Instron machine. A preheated oven attached to the Instron insured that the temperature of the test specimens never fluctuated more than a few degrees. Previous studies had shown that the compressor blades could experience a maximum, localized blade temperature in the neighborhood of 425°F or about 220°C. The test temperature was selected on this basis.

The manner in which thermal aging influences the flexural strength and modulus of phenolic resins reinforced with asbestos cloth and felt is shown in Figures 5 and 6, respectively. These results indicate that the acceptance or rejection of a candidate compressor blade material solely on its room temperature properties may be misleading. A more reasonable method of judging acceptability would be to thermally age the candidate material for at least 150 hours. After 150 to 200 hours, both the flexural strength and modulus thermally degrade in an apparent linear manner. It would be inappropriate at this time to present any empirical expression until a larger statistical sampling can be secured to verify the present data.

The composite material denoted as type 9579 and type 9517 asbestos felts in figures 5 and 6 were laminated by the same plastics fabricator and thus were made using the same phenolic resin. Type 9579 asbestos felt is a Grade AAAA that is 99% to 100% asbestos while Type 9517 is an Underwriters' Grade that is 80 to 85% asbestos. These results, along with many other laboratory tests, have verified that for a given phenolic resin, an increase in the amount of asbestos in the reinforcement will produce a corresponding increase in both the flexural strength and modulus. In addition, an increase in asbestos content is normally accompanied by a decrease in the thermal expansion. The Novatex material mentioned in the tables and curves is an AAAA asbestos cloth, which has a soap-like coating around each fiber. This coating is applied to reduce the amount of asbestos dust during processing of the raw asbestos into asbestos cloth.

The AA asbestos cloth reinforced phenolic composite materials, shown in Figures 5 and 6, have mechanical properties that are lower than the less pure Underwriters' Grade or Type 9517 asbestos felt reinforced phenolic (see Table 4). These composite materials were supplied by two different plastics manufacturers, and the one that supplied the asbestos cloth material has a slightly inferior phenolic resin.

TABLE 4

ASBESTOS CONTENT

| Grade | Asbestos Content by Weight |
|---|---|
| Commercial | 75% up to but less than 80% |
| Underwriters | 80% " " " " " 85% |
| Grade A | 85% " " " " " 90% |
| Grade AA | 90% " " " " " 95% |
| Grade AAA | 95% " " " " " 99% |
| Grade AAAA | 99% up to and including 100% |

Another variable which has a direct effect on strength and thermal degradation is interfacial bond strength between the resin and reinforcement. Felted materials have a much higher surface area than cloth, and therefore, theoretically should have a higher bond strength. Tests have indicated this to be true with phenolics, because, at processing temperatures, their viscosity is low enough to completely wet the reinforcement. The "2080" polyimide has a much higher viscosity and fabricators were unable to fully penetrate a felted reinforcement with this resin. The low strength of the Novatex laminate is attributed to the reduction of interfacial strength caused by the fiber coating.

The thermal degradation of two types of polyimide resin are shown in Figures 7 and 8. Both are pre-imidized, addition type polyimides. The difference in thermal degradation is due to the processing of the monomers prior to polymerization. The chemical difference between the two polyimides is beyond the scope of this paper, but the reason is that the Kerimid resin sacrifices the higher thermal

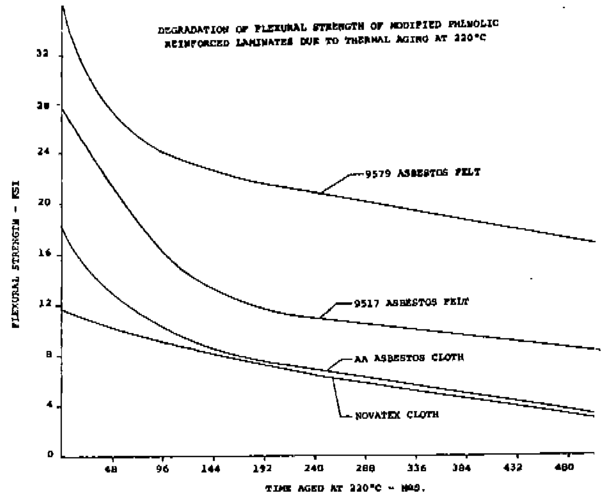



Table 5

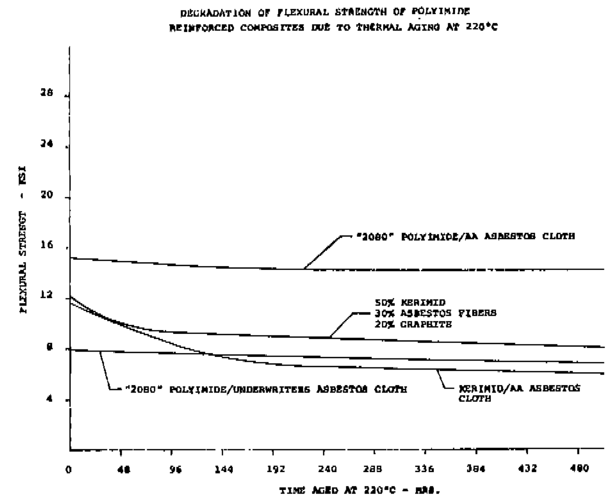



Table 7

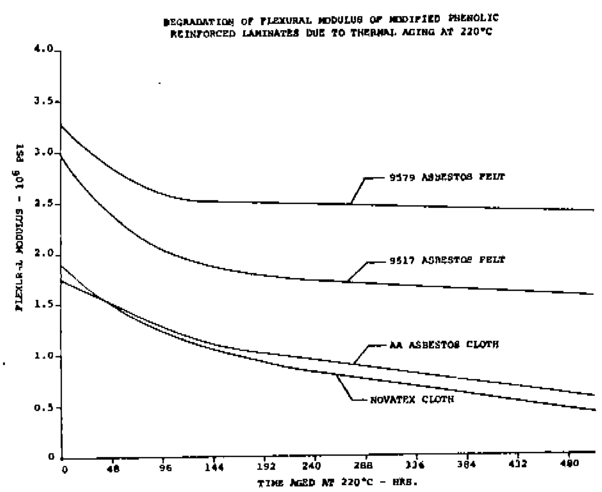



Table 6

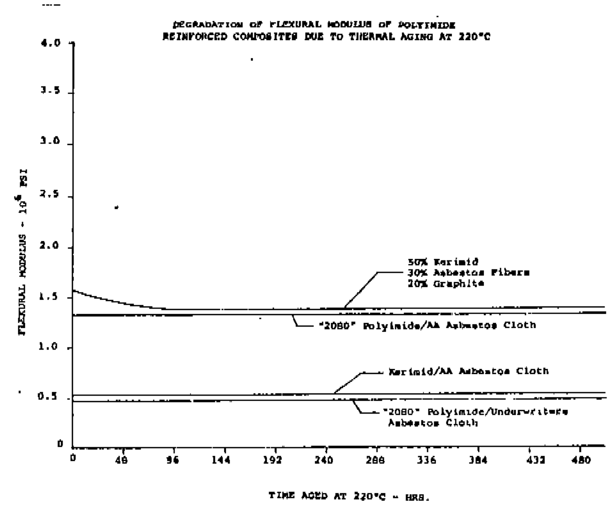



Table 8

stability and flexural strength of "2080" polyimide for processibility. This is defined as the ability of a resin to easily flow when heated. The drawback of "2080" polyimide is that it must be heated to between 650°F and 700°F to flow into a mold or completely encapsulate asbestos cloth in a laminate Kerimid overcomes this problem by slight changes in chemistry, which reduce the processing temperature 200°F-300°F. As stated, this also reduces the strength and thermal stability of this polyimide.

The change in chemistry also changes the Kerimid from a thermoplastic, like "2080" to a thermoset plastic. A thermoplastic is a material which softens and flows upon application of heat and pressure, and may be remolded after melting. A thermoset plastic material, once heated, reacts irreversibly so that subsequent applications of heat and pressure do not cause them to soften and flow.

The trend established for phenolic resins with regard to the purity of the asbestos reinforcement, also holds true for the polyimides. It is seen in Figure 7 and 8 that the 2080 polyimide reinforced with the AA asbestos cloth, which is 90% to 95% asbestos, has better flexural properties than the same resin reinforced with an Underwriters' Grade of asbestos cloth, which is 80% to 85% asbestos.

Unlike phenolic composite materials, both of these polyimides have excellent resistance to thermal degradation. Neither the flexural strength nor the flexural modulus of elasticity showed any significant decrease over the 500 hour thermal degradation test period. For this reason, the polyimide composites hold the greatest potential for improving the performance of compressor blade material.

## CONCLUSION

The main objective of this paper was to generate a greater interest not only in composite materials, but also in those problems associated with cyclic dynamic and thermal stresses, and the resultant failure, experienced by vanes in a rotary sliding vane compressor. A number of reinforced thermo-setting and thermoplastic composite materials were examined and their experimental mechanical properties were presented and discussed. The effect of thermal degradation on the flexural properties were examined and the superiority of reinforced polyimides under elevated temperatures was pointed out. It was an attempt to add to the ever growing knowledge of the static characteristics of composite materials.

It is recognized, however, that the failure mode of composite compressor blades cannot be explained through the use of one-time ultimate strength tests, but must be eventually accomplished under dynamic conditions generated through fatigue tests. Future research at Fuller will concentrate on the fabrication of a fatigue test fixture that will simulate cyclic dynamic and thermal stresses.

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